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ISOTHERMAL BAINITE IN AF1410

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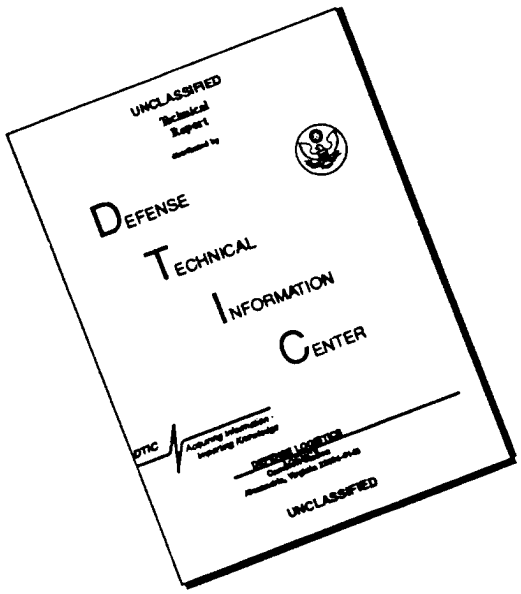

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13. ABSTRACT *(Maximum 200 words)*

The isothermal bainite transformation was identified in AF1410 by the use of thermomagnetic analysis methods. The formation of isothermal bainite in AF1410 has not been previously reported. Mechanical property test results indicate that isothermally processed AF1410 containing a mixture of bainite and martensite exceeds toughness properties of conventionally processed material containing 100% martensite. Moreover, the yield strength of isothermally processed material is the same as conventionally processed material.

Because the isothermal transformation to bainite occurs gradually over time, large internal strains are avoided. This contrasts with athermal martensite transformations where the rapid martensite transformation upon quenching often leads to distortion and cracking. The isothermal bainite in AF1410 can be exploited through the use of current isothermal processing methods to facilitate fabrication of the alloy. Isothermal processing of AF1410 components may permit most of the machining operations to be completed in the annealed condition (Rc 36) rather than in the peak aged condition (Rc 48).

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INTRODUCTION

The isothermal bainite transformation was identified in AF1410 through the use of Benét's Thermomagnetic Analyzer developed by Cote et al.[1] The formation of isothermal bainite in AF1410 has not been previously reported. Mechanical property test results indicate that isothermally processed AF1410 containing a mixture of bainite and martensite exceeds toughness properties of conventionally processed material containing 100% martensite with little sacrifice in strength.

AF1410 is characterized as an ultra high-strength steel (typically 1720 MPa tensile strength). This alloy was developed under Air Force sponsorship and has been used in critical applications such as airframe structural components, landing gear components, light armor plate, etc., where high strength and toughness are crucial. Secondary carbides, which precipitate in AF1410 during aging, give the alloy its high strength and consequently, make the alloy difficult to machine.

The isothermal bainite in AF1410 can be exploited through the use of current isothermal processing methods, e.g., molten salt baths, to facilitate fabrication of the alloy. Isothermal processing of AF1410 components may permit most of the machining operations to be completed in the full annealed condition (Rc 36) rather than in the peak aged condition (Rc 48). Additionally, potential distortion and cracking problems are avoided because isothermal processing is a gentle process that produces little distortion. Most important, the benefits of isothermal processing on AF1410 can be achieved without sacrificing in mechanical properties.

The chemistry and mechanical properties of AF1410 are provided in Tables 1 and 2. Extensive studies exploring isothermal bainite transformations have been conducted by Benét Laboratories. [1-4]

EXPERIMENTAL PROCEDURE

Test material for this study came from a hollow forging of AF1410 (4.5" I.D., 6.4" O.D., 11 ft. long). Pins 3/4" in length and 1/8" in diameter were fabricated from the forged material.

Isothermal Tests

All isothermal tests are conducted with pins electroplated with copper to protect the surface from oxidation and decarburization. Additional protection against oxidation is gained by conducting all tests in a 90% He/10% H_2 reducing atmosphere.

Test specimens are austenitized at 830°C for 10 minutes to fully transform the microstructure to austenite, a non-ferromagnetic phase. Test specimens are suspended in the austenitizing furnace by a fine chromel thermocouple wire. After austenitizing, the specimens are lowered into a "quench block" in the Thermomagnetic Analyzer. This is an essential feature of the system because it rapidly cools the specimens and avoids the otherwise slow asymptotic cooling to the isothermal temperature that can cause the formation of undesirable austenite

decomposition products. Upon placement in the quench block, a second thermocouple lead (alumel) is inserted through a small radial hole in the quench block to secure the specimens within the quench block and to dynamically monitor the cooling of the specimens. When the temperature of the cooling specimens is 40°C greater than that of the isothermal target temperature, the radial thermocouple is removed, allowing the specimens to be dropped into the isothermal furnace. This temperature discrepancy was experimentally developed to allow for further cooling of the specimen as it is dropped into the isothermal furnace. The in-situ isothermal transformation is monitored by measuring the change in the magnetization of the material (paramagnetic austenite to ferromagnetic bainite and martensite). The transformation time and magnetic response of the specimens is recorded on a PC for later data analysis. More detailed information regarding the Thermomagnetic Analyzer can be found in Reference 1.

The isothermal transformation studies were conducted at temperatures ranging from 280°C to 370°C in 10°C increments. Two additional tests were conducted at 220°C and 250°C.

Kinetics

All isothermal data were analyzed assuming Johnson-Mehl-Avrami (JMA) kinetics. JMA analysis has been extensively used in isothermal transformations to determine the mechanism(s) controlling nucleation and growth characteristics.

Mechanical Property Tests

Preliminary mechanical property tests were conducted on AF1410 material to compare the strength and toughness of conventionally processed material to isothermally processed material. Figure 1 shows two of the heat treatments examined in this experiment. Heat treatments were conducted on small test coupons of AF1410 material. The isothermal processing was conducted using two interconnected furnaces. After the test material was austenitized, it was transferred into an isothermal furnace. The mechanical properties examined included tensile, Charpy v-notch, and fracture toughness (J_{Ic}) tests. Charpy and fracture toughness tests were conducted at both RT and -40°C.

DISCUSSION

Isothermal Tests

Data from all isothermal transformation studies were analyzed to determine the volume fraction transformed versus time. The volume fraction transformed is related to the magnetic reading by the following relationship:

$$V_{fx} = \frac{M_0 - M_a}{M_{100} - M_0} \qquad (1)$$

where V_f, is the volume fraction transformed, M_0 is the minimum magnetization reading (representing 100% austenite), M_a is the actual magnetization reading at a given time increment, and M_{100} is the maximum magnetization reading (representing 100% martensite). The magnetic response is a sensitive function of the specimen length-to-diameter ratio (l/d). The present specimen geometry was selected to produce the linear relationship between the volume fraction transformed and the magnetic response as given in the above equation.

Figure 2 shows the isothermal transformation curves of AF1410 in the range of temperatures tested. Above 320°C, the curves were sigmoidal in appearance, representative of the nucleation, growth, and subsequent impingement of the transformation product. The incomplete transformation phenomenon was observed: As the temperature increased, less product transformed. These features are characteristic to both the isothermal bainite and isothermal martensite transformation. Figure 3 contains the identical curves as Figure 2, except that the abscissa has been magnified in order to observe the initial stages of the transformation. The tests conducted below 320°C revealed an instantaneous transformation. Also, below 320°C, the characteristic sigmoidal features are not present. These observances are attributed to the instantaneous formation of a small fraction of athermal martensite that caused increased nucleation and growth of the isothermal bainite. It is apparent, therefore, that the martensite start (Ms) temperature of AF1410 is approximately 320°C. This value for Ms corresponds reasonably well to that described in the literature [5, 6], in which Ms was reported in the range of 300-335°C. Thus, it is determined that the transformations occurring in AF1410 alloy are isothermal bainite and not isothermal martensite. Metallography was conducted to corroborate the formation of bainite as evidenced by the thermomagnetic test results; however, the results are inconclusive.

Kinetics

The kinetics of the isothermal bainite transformation in AF1410 were analyzed using conventional JMA equations. Porter and Easterling [7] and Christian [8] provide excellent discussions of JMA kinetics. Interpretation of the JMA equation provides the user with information on the nucleation and growth mechanisms that control isothermal transformation. The JMA equation is expressed in the form:

$$X = 1 - \exp(-kt^n) \tag{2}$$

where X is the extended volume fraction of product phase formed at time t (expressed in seconds), k is a rate constant highly dependent on temperature ($k = A\exp^{-Q/RT}$, where A is a constant, Q is an activation energy, R is the gas constant and T is the absolute temperature), and n is a constant assumed to be independent of temperature. Rearranging equation (2) gives:

$$\log\ln[1/(1-X)] = n\log t + \log k \tag{3}$$

where n is the slope of the line and $\log k$ is the y-intercept. The kinetics of AF1410, as seen in

Figure 4, do not exhibit straight-line behavior over the majority of temperatures tested. It is evident, therefore, that JMA kinetics were not adequate in describing the nucleation and growth characteristics of the isothermal bainite transformation in AF1410.

The non-linearity of the JMA results in AF1410 is not unusual. Previous tests on plain carbon and alloys steels [9-12] show similar, though not as dramatic, deviations from the expected linear JMA results. The deviation in straight-line behavior is believed to be associated with a change in the average growth rate, which can be affected by both the nucleation rate and growth geometry. Additionally, when using the Avrami equation, a constant growth rate is inherently assumed.

The kinetics of AF1410 are complex because of the high percentage of alloying elements present. Chemical segregation (i.e., banding) may cause the nucleation and growth kinetics to become altered compared with homogeneous plain carbon steels. Further complications may be introduced by the type of segregated alloying elements present in the microstructure. For example, Co shifts the "C" curve to the left, while other alloying elements shift the "C" curve to the right.

Variations in solute concentration, grain size, etc., can alter the growth rate during the isothermal transformation and lead to non-JMA kinetics. This change in growth rate was addressed by both Rath [13] and Cahn and Hagel.[14] Rath described JMA kinetics as being a subset of a more universal equation that describes more general isothermal transformations. In Rath's formulation, a variable growth rate is allowed. In using Rath's universal kinetic equation, isothermal transformations can be analyzed to determine if the growth rate is constant or variable. This equation may provide valuable insight on the kinetics of the isothermal bainite transformation in AF1410.

Comments on Activation Energies

It is well known that the transition from upper to lower bainite occurs universally at approximately 350°C. Therefore, it is postulated that examining the kinetics of the bainite transformation above and below this temperature will determine the activation energies for upper and lower bainite. Several experiments have been conducted [9-12] using a chemical rate equation based on equation (2). The derivative of equation (2) was taken to give an expression of the rate of the bainite transformation:

$$\frac{dX}{dt} = nkt^{n-1}\exp(-kt^{n}) = nkt^{n-1}(1-X) \qquad (4)$$

so that:

$$\frac{dX}{dt} = C exp^{-Q/RT} \tag{5}$$

where C is a function of X and independent of temperature, Q is the activation energy, R is the gas constant, and T is the absolute temperature.

These activation energies are not constants if the mechanisms for nucleation and/or growth change during the isothermal transformation, or if the mechanism(s) change during a temperature range of interest, i.e., if the slope of the JMA plot does not remain constant. In typical time-temperature-transformation (TTT) diagrams, "C" curves are produced because of two competing activation energies, an activation energy for nucleation (Q_n) and an activation energy for diffusional growth (Q_g). At high temperatures, nucleation is limited and diffusional growth is dominant; conversely, diffusional growth is limited and nucleation is dominant at low temperatures. The lowest activation energy is associated with an intermediate temperature at which both nucleation and growth are active. These competing nucleation and growth mechanisms lead to an overall activation energy that constantly changes with temperature. It is thus difficult to acknowledge the validity of the activation energies of upper and lower bainite experimentally determined when the slopes of the JMA plots did not remain constant. It may be feasible to perform tests where either the nucleation or growth mechanisms dominate. One method of accomplishing this is to conduct isothermal tests at sufficiently low temperatures to ensure early site saturation. Therefore, only the growth mechanism is monitored during the transformation. If the average growth rate and the shape of the growing phase do not change, a meaningful activation energy may be extracted.

Mechanical Property Tests

Table 3 contains the mechanical properties results for conventionally processed AF1410 (from product literature and actual testing conducted at Benét) compared with isothermally processed AF1410.

A slight decrease in the 0.2% yield strength (approximately 3%) of the isothermally processed material was measured compared with conventionally processed material. However, with the decrease in yield strength, there was a corresponding 10% increase in toughness at RT compared with conventionally processed material. All fracture toughness tests were J_{Ic} tests

conducted in accordance with ASTM E-813. These data were converted to K_J data by the relation:

$$K_J = \sqrt{\frac{EJ_{Ic}}{1-\nu^2}} \tag{6}$$

where E is Young's Modulus, J is the J-integral fracture toughness expressed in units of MN/m (in•lb/in^2), and ν is poisson's ratio. K_J has the units of MPa$\sqrt{m}$ (ksi$\sqrt{in}$). Assuming the universal values for E and ν for steels of 207 GPa (30x10^6 psi) and 0.3, respectively, results in the following relationships:

$$\begin{aligned} K_J &= 477\sqrt{J_{Ic}} \quad (MPa\sqrt{m}) \\ K_J &= 5.74\sqrt{J_{Ic}} \quad (ksi\sqrt{in}) \end{aligned} \tag{7}$$

Further isothermal tests using molten salts are necessary before making firm conclusions.

SUMMARY

Isothermal bainite has not been previously reported in AF1410 alloy. Isothermal bainite was identified using thermomagnetic analysis. Isothermal test temperatures ranged from 220-370°C. Plots of volume fraction formed versus time revealed the typical sigmoidal shape common to isothermal bainite. The kinetics of the isothermal bainite transformation were examined using the JMA equation. Because the JMA plots were not linear, these equations were not sufficient to describe the nucleation and growth characteristics of isothermal bainite in AF1410. A more universal kinetic equation is currently being examined for the kinetics in AF1410.

Preliminary mechanical properties tests comparing isothermally processed material with conventionally processed material indicate no significant sacrifice in strength and an improvement in toughness in the isothermally processed material over the conventionally processed material.

The identification of isothermal bainite in AF1410 can be exploited through the use of current isothermal processing methods, e.g., molten salt baths, to facilitate fabrication of the alloy. Isothermal processing of AF1410 components will enable the majority of the machining operations to be completed in the full annealed condition (Rc 36) rather than in the peak aged condition (Rc 48). Additionally, potential distortion and cracking problems will be eliminated because isothermal processing produces little distortion. These benefits of isothermal processing on AF1410 can be achieved without sacrificing mechanical properties.

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Table 1. Chemical composition of AF1410 (wt. %)

Alloying Element	Typical Chemistry (wt. %)
C	0.16
Mn	0.01
Si	0.01
S	.005
P	.008
Cr	2.00
Ni	10.00
Co	14.00
Mo	1.00
Fe	Balance

Table 2. Typical mechanical property results on conventionally processed AF1410

Mechanical Properties	Product Literature Conventional H.T.*	Benét Conventional H.T.
UTS MPa; [Ksi]	1620 [235]	1682 [244]
0.2% YS MPa; [Ksi]	1517 [220]	1524 [221]
Elongation	12%	-
%RA	60%	-
Charpy (RT) J; [ft•lb]	-	77 [57]
Charpy (-40) J; [ft•lb]	-	64 [47]
K_{Ic}** (RT) MPa$\sqrt{m}$; [Ksi$\sqrt{in}$]	143 [130]	210 [191]
K_{Ic}** (-40) MPa$\sqrt{m}$; [Ksi$\sqrt{in}$]	-	187 [170]

[ ] English Units

*Unimach AF1410 High Strength Steel Technical Data Sheet, Universal-Cyclops Specialty Steel Division, Pittsburgh, PA, 1978.

**In Bénet fracture tests J_Q data were converted to K_{JQ}.

Table 3. Preliminary mechanical property results on conventionally processed AF1410 vs. isothermally processed AF1410

Mechanical Properties	Product Literature Conventional H.T.*	Benét Conventional H.T.**	Benét Isothermal H.T.
UTS MPa; [Ksi]	1620 [235]	1682 [244]	1708 [248]
0.2% YS MPa; [Ksi]	1517 [220]	1524 [221]	1469 [213]
Elongation	12%	-	-
%RA	60%	-	-
Charpy (RT) J; [ft•lb]	-	77 [57]	79 [58]
Charpy (-40) J; [ft•lb]	-	64 [47]	66 [49]
K_{Ic}** (RT) Mpa$\sqrt{in}$; [Ksi$\sqrt{in}$]	143 [130]	210 [191]	230 [209]
K_{Ic}** (-40) Mpa$\sqrt{in}$; [Ksi$\sqrt{in}$]	-	187 [170]	-

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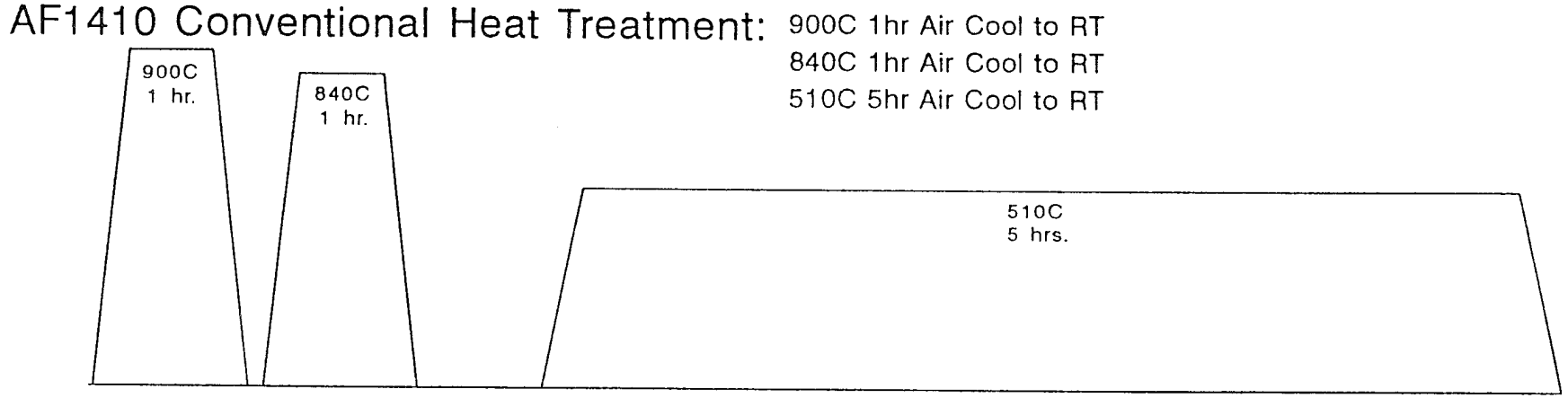


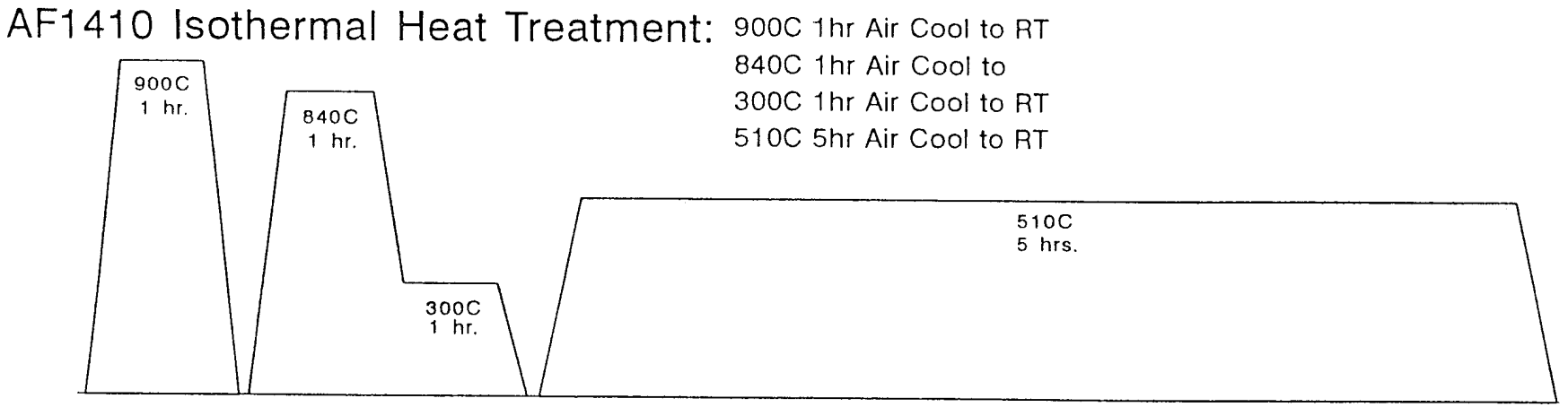


Figure 1. Heat treatments used for preliminary mechanical property tests

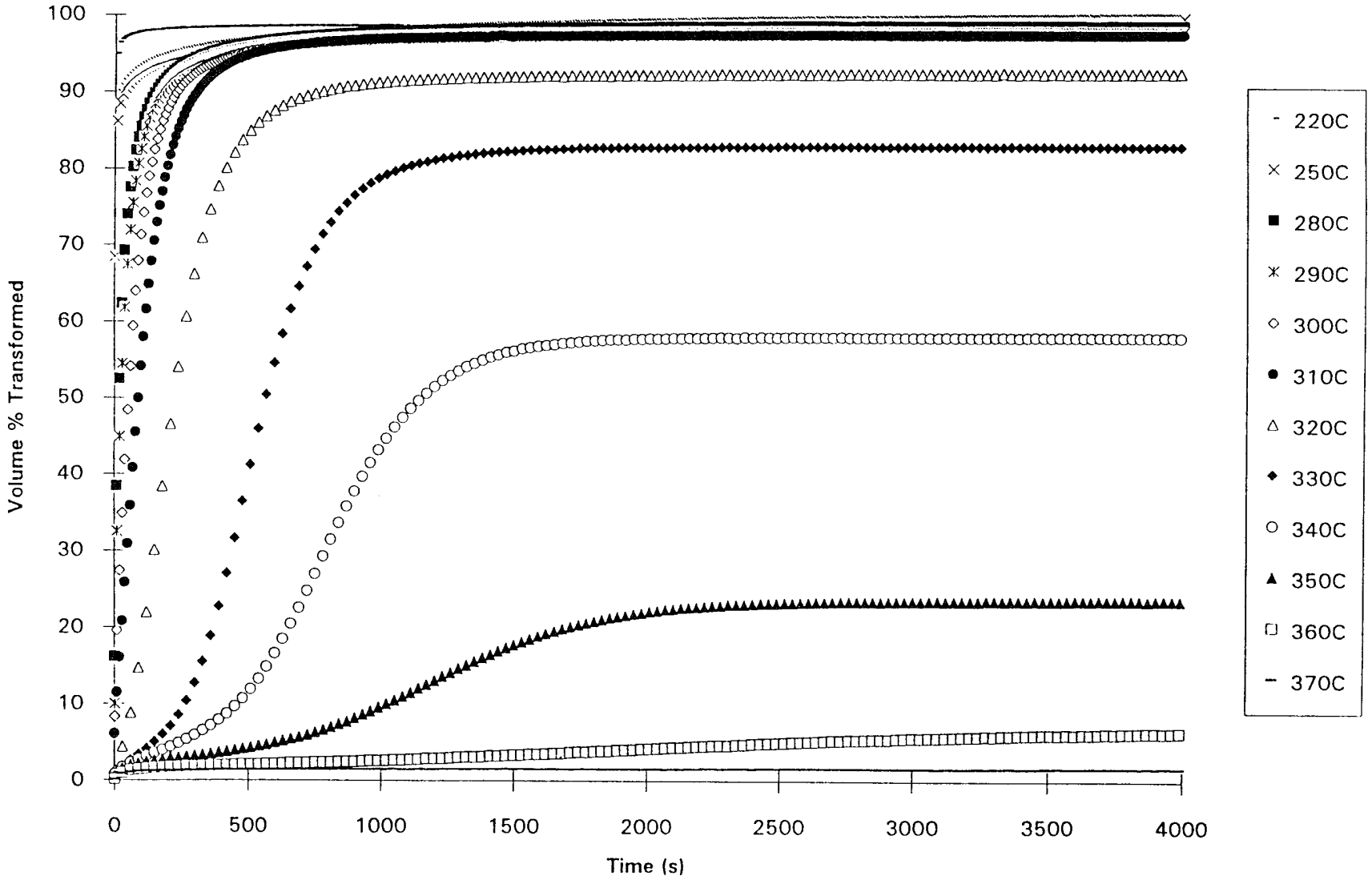
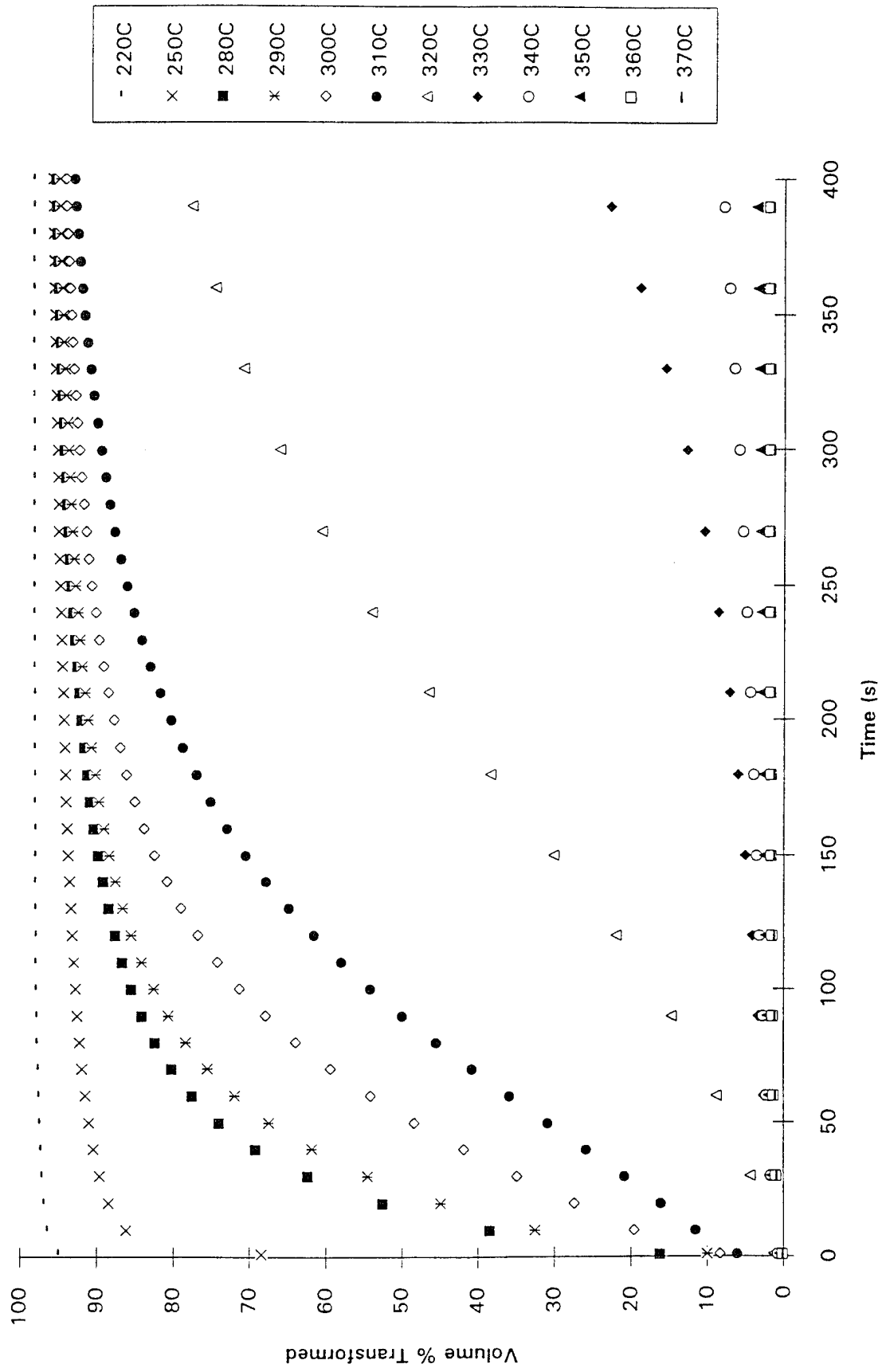


Figure 2. Isothermal bainite transformation curves for AF1410



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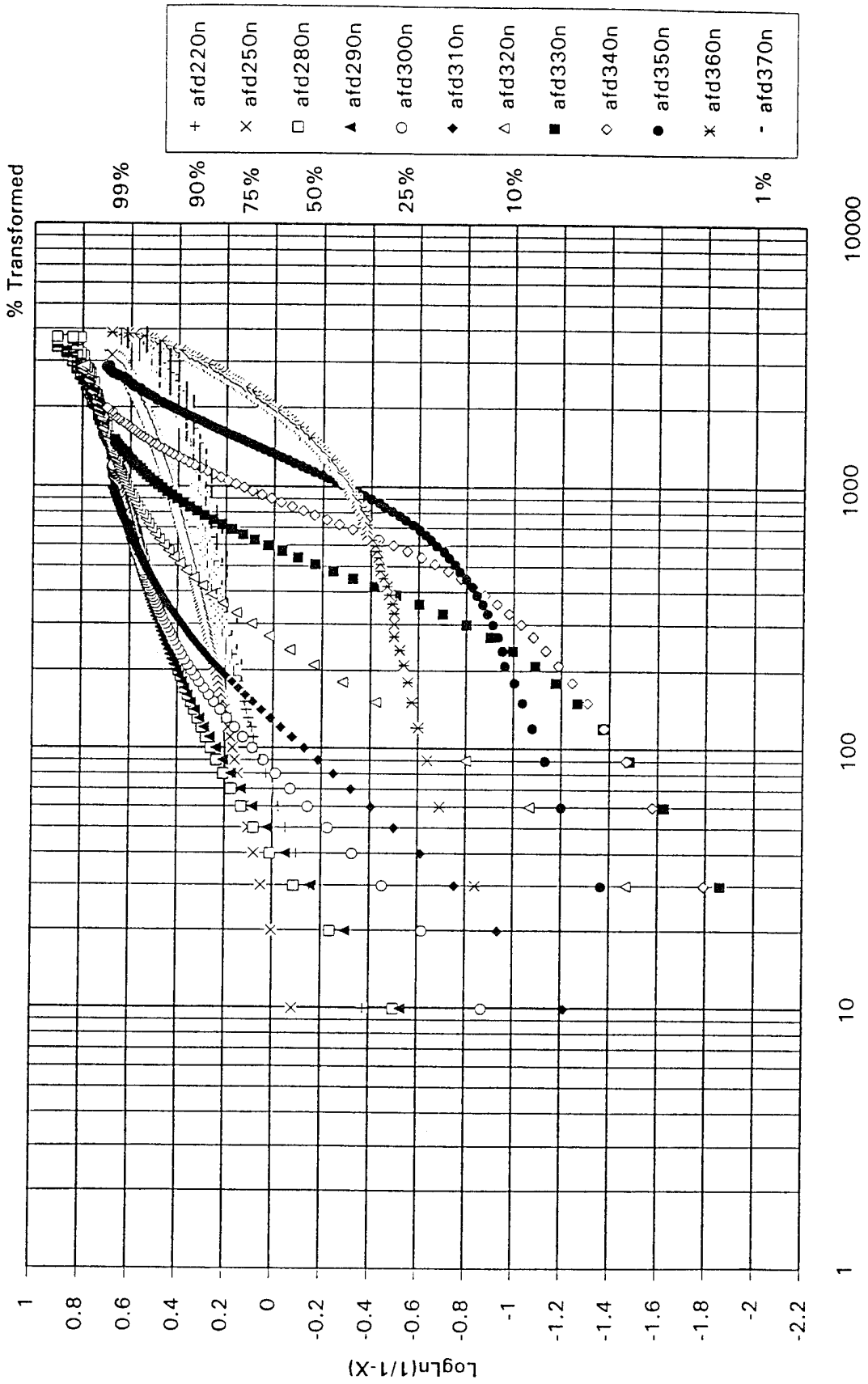

Figure 4. Johnson-Mehl-Avrami plots of isothermal bainite transformations in AF1410

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